Beamlet Pulsed-Power System

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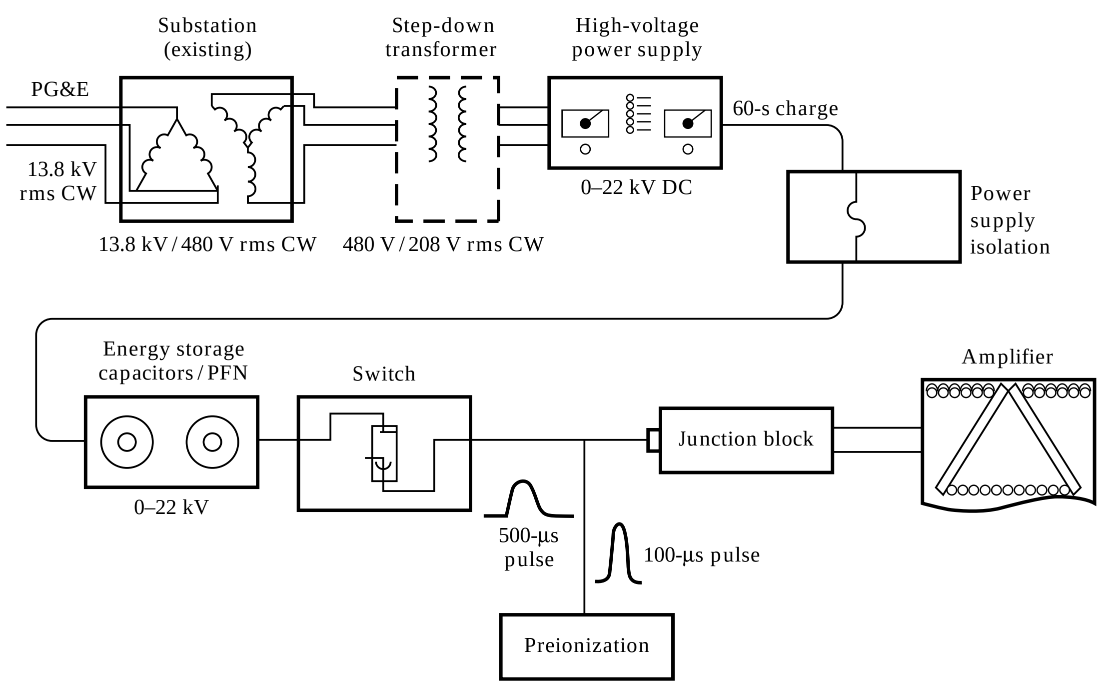
Introduction

The 13-MJ Beamlet pulsed-power system provides power to the 512 flash lamps in the cavity and booster amplifiers. Since the flash lamps pump all of the apertures in the 2×2 amplifier array, the capacitor bank provides roughly four times the energy required to pump the single active beam line. Figure 1 is a block diagram illustrating the main pulsed-power subsystems. During the 40 s prior to the shot, the capacitors are charged by constant-current power supplies. Ignitron switches transfer the capacitor energy to the flash lamps via coaxial cables. A preionization system triggers the flash lamps and delivers roughly 1% of the capacitor energy 200 µs prior to the main discharge. This is the first time flash-lamp preionization has been used in a large facility. Preionization improves the amplifier efficiency by roughly 5% and increases the lifetime of the flash lamps. Figure 2 shows a typical Beamlet current pulse. LabVIEW[1] control panels provide an operator interface with the modular controls and diagnostics. Figure 3 shows one of the four aisles of capacitor circuits and the wall of equipment racks containing the controllers, triggers, and charging supplies.

Table 1 shows the primary pulsed-power requirements. The system is assembled from 32 independent modules, each capable of driving 16 flash lamps to 30% of their explosion limit. The circuit architecture (Fig. 4) is similar to Nova's, but the Beamlet system demonstrates several features of the proposed National Ignition Facility (NIF) pulsed-power design. To improve the reliability of the system, high-energy-density, self-healing, metallized dielectric capacitors are used.

FIGURE 1. Block diagram of the Beamlet pulsed-power system. (40-00-0591-1686pb01)



High-frequency, voltage-regulated switching power supplies are integrated into each module on Beamlet, allowing greater independence among the modules and improved charge voltage accuracy, flexibility, and repeatability. On Nova, by contrast, many modules are charged with a single large unregulated power supply with high-voltage diodes to provide isolation. Failure of these diodes allows very large amounts of energy to be released in a single fault.

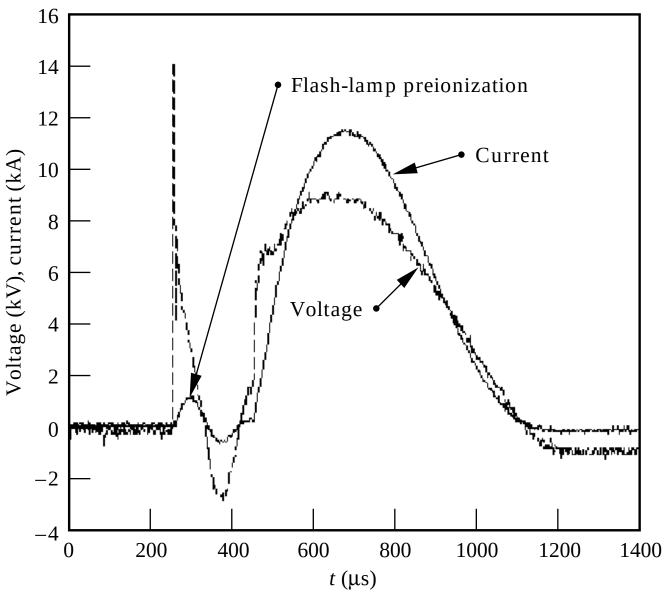


FIGURE 2. Typical flash-lamp current and voltage waveforms during the firing of the Beamlet pulsed-power system. (70-50-1294-4019pb01)

Capacitor Circuits

The Beamlet capacitor bank contains 256 capacitor circuits, each of which stores 52 kJ at 22 kV (Fig. 5). An additional 32 preionization circuits each store 3.6 kJ. The main capacitor circuits include: a single high-energy-density capacitor, a manual disconnect switch, a high-voltage fuse, a pulse-shaping inductor, a charge resistor, and a spark-gap. The capacitor-inductor combination forms the 500-μs current pulse that drives the flash lamps. The manual disconnect switch disconnects the capacitor circuit from the remainder of the module and shorts the capacitor terminals. The high-voltage fuse, rated to carry 45,000 A^2s and open at 180,000 A^2s, is designed to protect the flash lamps from a failure that could exceed their explosion energy rating. This failure mode could occur in the event of a capacitor short circuit prior to triggering the switches. The spark-gap limits the magnitude of the voltage transient generated by the inductor when the fuse clears.

The energy storage capacitors, developed for Beamlet, use the metallized dielectric electrode technology. This technology gives the capacitors improved energy density and reliability in ICF applications and is included in the conceptual design for the proposed NIF pulsed-power system. Figure 5 is a photograph illustrating the evolution of capacitor technology for ICF pulsed-power systems over the past 20 years. The Beamlet capacitor stores 4 times the energy of the Nova capacitor, and 15 times that of Shiva, in roughly the same volume. The Beamlet capacitors have a different construction and failure mechanism compared to conventional

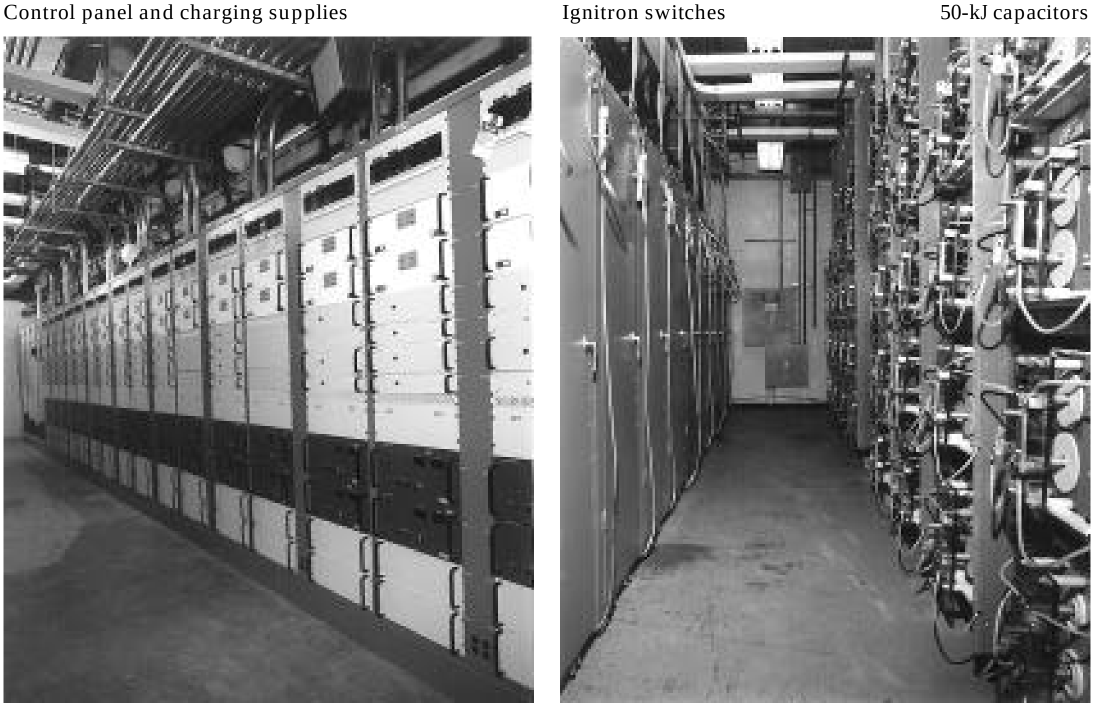


FIGURE 3. Photograph of the pulsed-power control panel and one of the four aisles that contain the ignition switches and 50-kJ capacitors. The total bank's stored energy is 12.8 MJ at 20 kV. (70-50-0294-0465pb01)

foil-electrode capacitors. The improvements in the Beamlet metallized electrode result primarily from the self-healing characteristic of the dielectric system. The electrode is a thin (20-nm) layer of Al deposited onto the dielectric. If the dielectric is punctured, the resulting current flow vaporizes the electrode in the vicinity of the fault so that the short is cleared, or "healed," resulting in a small reduction in capacitance. In a conventional capacitor, the punctured dielectric would result in a short circuit and catastrophic capacitor failure. Thousands of healing events may occur before the capacitance is significantly reduced. Failure is typically defined as a 5% reduction in capacitance from the nominal value for metallized dielectric capacitors. Energy density is improved, since the capacitors may be operated near the intrinsic dielectric strength of the material, rather than derated to account for material or manufacturing flaws. System reliability is improved by the "soft" failure mode of the metallized capacitors. The capacitors suffer a gradual capacitance loss, rather than a catastrophic short-circuit. This effect can be monitored directly by periodically measuring the capacitance, or inferred by recording the peak current on each shot and detecting a reduction resulting from reduced capacitance. The second method is implemented on Beamlet. This information allows the operator to monitor the status of the capacitors during normal operation, and to replace aging capacitors during scheduled maintenance times.

Qualification and acceptance tests were performed on the Beamlet capacitors to validate their performance. Qualification testing consisted of a life test at simulated Beamlet operating conditions (22 kV, 13 kA), including 25 fault-mode shots (22 kV, 24 kA, 70% reversal). Acceptance tests were performed on 7 lots of approximately 40 capacitors per lot. Each capacitor received a 25-shot functional test at nominal Beamlet operating conditions, and a DC high-voltage test of the bushing-to-case insulation. Three capacitors from each lot received an additional 1000 shots, and one of those an additional 9000 shots. No failures were observed in any of the tests, although due to a manufacturing defect, one of the capacitors dropped 4% from nominal during the 10,000-shot test. Periodic capacitance measurements were conducted to monitor the capacitor status. Figure 6 shows the results of a typical life test. A Weibull statistical analysis of the qualification and acceptance test data was used to predict the reliability

FIGURE 4. Simplified schematic of a Beamlet capacitor-bank module. (40-00-0591-1684pb01)

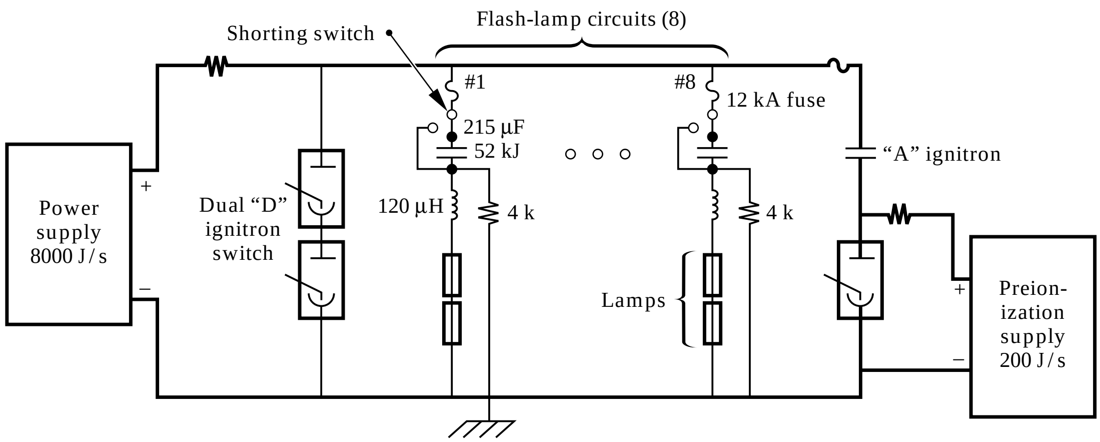


TABLE 1. Major requirements of the Beamlet pulsed-power system.

Item	Requirement	Purpose
Maximum delivered energy	9.1 MJ	Operates 512 Beamlet flash lamps at $f_x = 0.3$
Explosion fraction range	$0.2 \le f_x \le 0.3$	Operating flexibility
Preionization energy	0.3 J/cm2 of lamp bore	215 J/lamp, 90 µs pulse
Main pulse length	500 µs	3 $(LC)^{0.5}$
Maximum repetition rate	3 shots/hr	Amplifier characterization shot rate
Bank lifetime	$>10^3$ shots at $f_x = 0.3$, or $>10^4$ shots at $f_x = 0.2$	Capacitors are limiting component. End of life determined by 5% capacitance reduction
Number of capacitor modules	32	Allows separate drive energies of inner and outer flash-lamp arrays
Charge voltage repeatability	±0.5%	Minimize shot-to-shot gain fluctuation

f_x = explosion fraction = lamp energy/theoretical limit.

LC = (L) circuit inductance, (C) circuit capacitance.

of the capacitors.[2] The analysis showed that we can expect a mean-time-between-failures (MTBF) of 2000 shots over the expected 5000-shot life of the Beamlet. If the same capacitors were used in the larger NIF system, a capacitor would require replacement roughly every 100 shots over the same period.

Switches

The Beamlet switch assembly is an evolution of the Nova design. Two size "D" ignitrons, in series, switch the 8 circuits of each module in parallel. The switches operate at 22 kV, 100 kA, and transfer 35 C per shot. A size "A" ignitron is added to the assembly to discharge the preionization circuit. The single tube is operated at up to 22 kV, 11 kA peak current.

FIGURE 5. Photograph comparing Shiva, Nova, and Beamlet capacitors. The capacitor energy storage density has increased 15-fold in the 20 years since Shiva was built and 4-fold since Nova was built. (70-50-0594-2523pb01)

Charging Supplies

The Beamlet design maximizes system modularity by embedding the charging supplies within each module. In this way, the "copper" connections between modules are limited to common AC power and grounds. This approach is especially important in large systems such as the proposed NIF, in which it is desirable to build a system from 200 independent 1.6-MJ capacitor banks, rather than a single 320-MJ capacitor bank.

This approach has been made practical by the development of efficient, reliable, high-frequency switching power supplies over the past decade. These supplies use advanced insulated-gate bipolar-transistor-power semiconductor devices and reliable architectures such as the series-resonant-inverter. The high operating frequency enables the use of efficient ferrite magnetics, resulting in small size and weight. The Beamlet charging supplies are approximately 30 times smaller than the equivalent supplies used on Nova.

The main capacitors in each module are charged by a supply with an average charge rate of 10 kJ/s, which delivers up to 20 kW at the end of the charge cycle. The output current is a constant 900 mA until the supply reaches its regulation point. It then holds the capacitors at a constant voltage until they are discharged. Additional circuitry is needed to protect the supplies in the event of a bank fault that results in reversal of the capacitor voltage. Voltage reversal tends to drive large values of current through the small diodes in the output rectifier of the charging supply, resulting in failure of the diodes. The circuit shown in Fig. 7 protects the supplies from bank faults. The diode stack diverts the fault current, while the 50-Ω resistor limits the fault current to a safe level for the diodes. The fuse limits the energy deposited in the charging supply in the event of a short circuit in the supply itself.

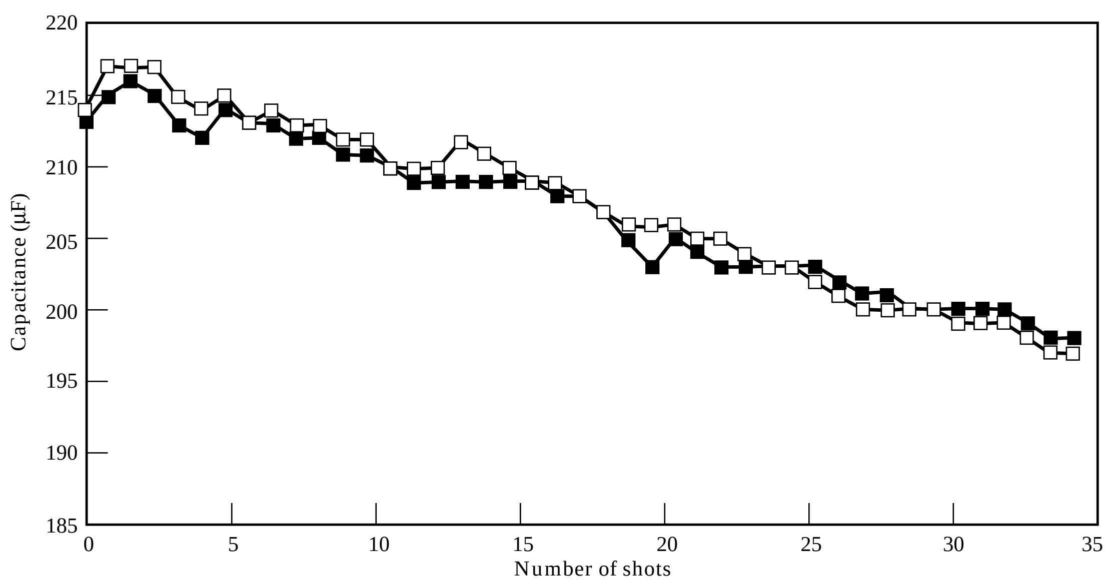


FIGURE 6. Results from lifetime tests on two Beamlet 50-kJ dielectric capacitors. The data show the slow decay in capacitance with the number of shots. (70-50-1294-4018pb01)

The preionization capacitors are charged by a small, 200-J/s power supply similar in design to the large supplies. A 50,000-Ω resistor is placed in series with the output to protect the supply from capacitor voltage reversal. A series of equipment racks contain the charging supplies, triggers, and controls for the system. Each rack bay contains the controls, chargers, and triggers for two capacitor modules.

Power Transmission

Coaxial cables are used to deliver the capacitor energy from the bank to junction blocks near the amplifiers. The length of the cables varies from 25 to 70 m. We chose a 50-Ω, high-voltage coaxial cable (RG-217) since it was used on Nova and Shiva, and many excess fittings and terminators were available for use on Beamlet. This cable, however, resulted in high resistive losses at the elevated Beamlet operating currents. As much as 30% of the capacitor energy is lost in the cables at the highest explosion fractions and longest cable lengths.

The coaxial cables terminate in junction blocks in the Beamlet center tray near the amplifiers. The junction blocks affect the transition from the coaxial cable to the flexible twisted-pair cable, which delivers the energy the last several meters to the flash-lamp cassettes in the amplifier. A custom twisted-pair cable was developed for Beamlet, since the magnetic forces due to increased current caused failures in the Nova-type cables during prototype tests. The cable is made from flexible, silicone-insulated wires that are twisted and covered with a layer of mylar and a strong nylon braid to contain the magnetic forces. A PVC jacket covers the assembly.

Controls and Diagnostics

As shown schematically in Fig. 8, a hierarchical computer system controls the Beamlet pulsed-power system. A central control computer, located in the Beamlet control room, provides a graphical LabVIEW operator interface, data archiving, timing control, and coordination of pulsed-power system operation with other Beamlet subsystems. In the capacitor bank, single-board computers receive high-level commands from the central computer and control bank operation through the control-interface chassis. The single-board computers, their fiber-optic communications system, and the control interface chassis were assembled from industrial process control components to achieve a robust and inexpensive system. Conceptually, this design is very similar to the design of the power conditioning system controls for the proposed NIF.

The principal diagnostic for the Beamlet pulsed-power system is measurement of peak current in each flash-lamp string. The current in each flash-lamp pair is detected by a current transformer. The current-peak-detector chassis in each pulsed-power module provides analog peak-detection measurements that are digitized by the control interface chassis and transferred to the central control computer.

The current-peak-detector chassis also performs a fault protection function. In the event that a capacitor should short while charged, the other capacitors in that module would discharge through it into its lamp string. If the fuse fails to open properly, this fault may result in the explosion of the lamp and serious damage to nearby optics. This failure mode has occurred on Nova and is responsible for nearly all of its flash-lamp explosions to date. To prevent this on Beamlet, the current-peak detector sends an indication of the onset of current flow to the trigger-distribution chassis. If current flow is detected before the system triggers have been generated,

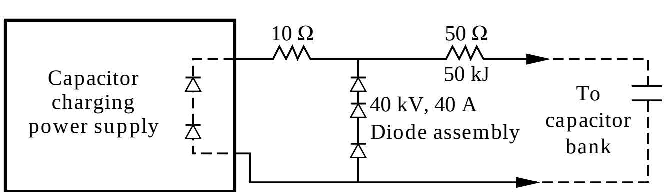


FIGURE 7. A combination of resistors and diodes protects the charging supply in the event of capacitor bank faults. (70-50-1294-4017pb01)

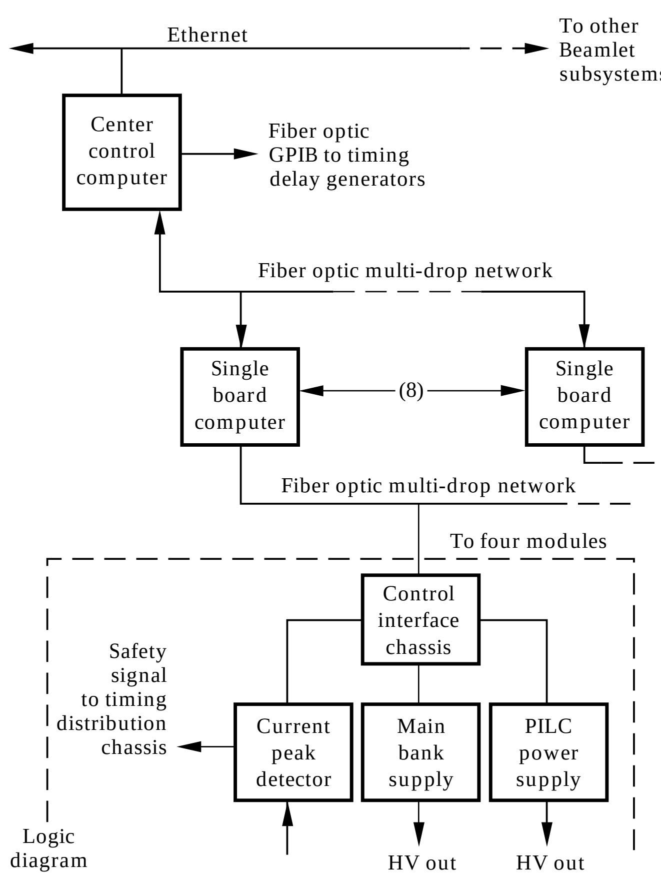


FIGURE 8. Schematic diagram of the pulsed-power control system. (70-50-1294-4016pb01)

the trigger-distribution chassis fires the main bank ignitrons. This diverts the current flow from the failed circuit to the ignitron, thereby preventing the flash-lamp explosion energy from being reached.

The single-board computers also perform a fault protection function by monitoring the value of the voltage on the preionization power supply. If significant charge were left on the preionization capacitors by, for example, an aborted shot, and then the main bank were charged, the output of the preionization supply would be subjected to the sum of the voltages, which could exceed the maximum voltage design rating of the supply. If the single-board computers detect excessive preionization voltage, they automatically shut off the main bank charging supply to protect the system.

The Beamlet timing controls are based on commercial delay generators. A master radio-frequency clock and the 0.2-Hz regenerative amplifier trigger are distributed building-wide on a system of transformer-isolated coaxial cables. A fiber-optic extended GPIB network connects all the delay generators to the Beamlet pulsed-power system's central control computer. The resulting system meets a specification of 250 ps peak-to-peak jitter.

Summary

To date, the reliability of the Beamlet pulsed-power system has been very good. During the first 700 system shots, no failures occurred in the high-current circuitry. The ignitron pre-fire rate was high during the first 100 shots until the weak tubes were culled from the system. A design defect in the preionization supplies resulted in a high initial failure rate. The addition of external components solved that problem. No measurable reduction in capacitance has been detected in any of the metallized dielectric capacitors.

Notes and References

1. LabVIEW, a data acquisition and control programming language, National Instruments Corp., 6504 Bridge Point Parkway, Austin, TX, 78730–9824.
2. D. W. Larson, "The Impact of High Energy Density Capacitors with Metallized Electrode in Large Capacitor Banks for Nuclear Fusion Applications," Digest of Technical Papers, *Ninth IEEE International Pulsed Power Conference,* Albuquerque, NM, June 21–23, 1993.